Global Food Security 16 (2018) 138–149

Contents lists available at ScienceDirect

Global Food Security

journal homepage: www.elsevier.com/locate/gfs

Drying tendency dominating the global grain production area

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ARTICLE INFO

Keywords:
Drought variation
SPEI
Crop yield
Food security
Global grain production area

ABSTRACT

Drought is considered an environmental disaster with a direct and devastating impact on agriculture. However, little research focuses on climate change related drought variations across the global grain production area (GGPA). Thus, the variation of crop yield across different grain production regions that experience severe drought remains inadequately studied. We analyzed drought variations across the GGPA to study the impacts of severe droughts on the yields of four major crops (maize, rice, wheat, and soybean). This analysis was based on the Standardized Precipitation Evapotranspiration Index (SPEI) and the crop yield dataset from 1951 to 2011. The results indicated that the entire GGPA experienced a significant increase in drought duration, impacted area, and severity of hazards. There was an average of 2.2 dry months and the dry area increased by 1.109% per decade. Regional variations existed across the GGPA, although the majority presented a tendency to increasing drought. Southern and Northern America tended to become wetter, while Eastern Asia, Southern Europe, and Africa (except for Eastern Africa) tended to become dryer. Developing countries and regions are generally more susceptible to extreme droughts and suffer more losses than developed countries and regions.

1. Introduction

Drought is one of the primary environmental disasters and imposes significant effects on global agriculture, global economy, water supplies, and environmental ecosystems (Piao et al., 2010). Droughts with high frequencies, long durations, and large ranges occur almost yearly across the globe, even in wet and humid regions (Mishra and Singh, 2010; Chen and Sun, 2015). According to incomplete statistics, the global percentage of dry area has increased by about 1.74% per decade from 1950 to 2008 and the number of drought events and corresponding economic losses have increased rapidly since 1960 (Fig. 1, EM-DAT, 2016). Worse still, droughts are expected to increase due to global warming (Cook et al., 2014) and therefore, drought has become a looming threat to human survival and global development (Dai et al., 2011; Trenberth et al., 2013). Focusing on drought variations will provide an epistemological foundation to prepare and understand drought events and their consequences. Increasing attention has recently been directed toward global drought variations, due to the threats posed by drought to global grain security (Hoerling et al., 2010; Sheffield et al., 2012; Dai, 2013; Beguería et al., 2014; Trenberth et al., 2014; Deo et al., 2017). Two current mainstream viewpoints have been presented on global drought changes that occurred over the past few decades, resulting from differences in the length of time series of climatic datasets and drought metrics (Trenberth et al., 2014). This has led to a debate over the severity of global droughts, and some researchers have suggested that global droughts are following an increasing trend (including occurrence, duration, intensity, and affected areas) due to global climate change (Dai, 2013). Other researchers have suggested that global droughts have seen little change over the past 60 years (Sheffield et al., 2012). Both viewpoints have been supported by a large number of studies, although the contradictory arguments can confuse policy-makers and practitioners of the food sector as both groups strive to be proactive and adaptive to current drought hazards.

The 4th and 5th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) have predicted that grain yield in middle to high latitude areas will see some increase if the temperature increase by 1–3 °C while it will decrease if this increase in temperature exceeds a certain threshold. Food crops are particularly susceptible to climatic changes; therefore, the impact of such changes on grain production may be quite severe. Recent research typically focuses on the response of crop yields on either a regional or global scale and in response to climate change (e.g., precipitation, temperature, and evapotranspiration) (Lobell et al., 2011; Asseng et al., 2013; Wheeler and Von Braun, 2013; Ray et al., 2015). These studies could reveal how crop yield has been

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https://doi.org/10.1016/j.gfs.2018.02.001
Received 28 August 2017; Received in revised form 2 February 2018; Accepted 3 February 2018
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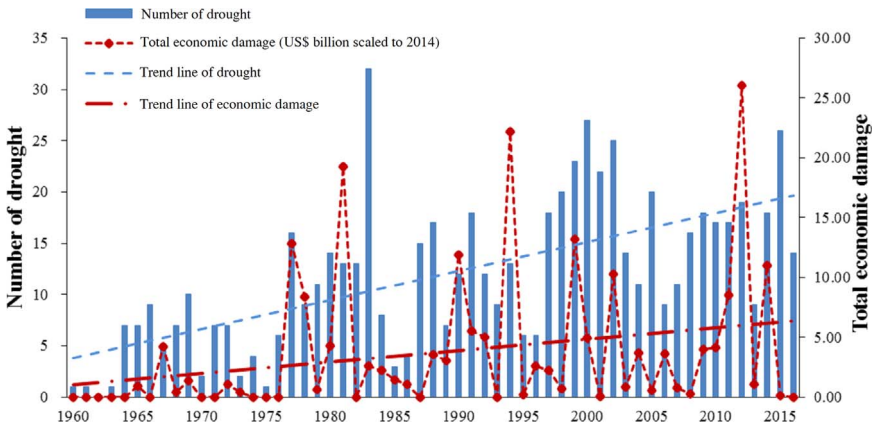

Fig. 1. Number of droughts and total economic damage since 1960 from around the world. The data was available from the Emergency Events Database (EM-DAT).

affected historically by climatic anomalies and would furthermore allow the prediction of crop yield changes over time with regard to global climate change. Among meteorological disasters, there is no doubt that drought disasters have become the focus of recent research because it could result in severe damage due to high temperature, low soil moisture, and high evapotranspiration, originating from the reduction of agricultural water. Therefore, drought could potentially damage water resource systems, which has the potential to destabilize entire food systems, thus threatening local or global food security (Dai, 2011; Lesk et al., 2016). Furthermore, the majority of evidence indicates that droughts are expected to increase in frequency and as well as in severity in the future (Sheffield et al., 2012; Lesk et al., 2016). To develop effective countermeasures, an evaluation of the effects of droughts on crop yields is both necessary and significant, while still ensuring stable crop production.

The global grain production area (GGPA) is directly connected to food security and is important when ensuring adequate crop production that meets the requirements of the growing population as well as the socio-economic development of entire regions. Intensive, large-scale droughts have recently occurred in the GGPA, which could threaten agricultural production and global food security, particularly for the four major crops (i.e. maize, rice, wheat, and soybean) (Mishra and Singh, 2010; Geng et al., 2016). Few studies to date have quantitatively examined the impacts of drought on the GGPA in response to global climate change. Controversy exists about the severity of the drought in GGPA. The variations of crop yields caused by different droughts across different sub-areas of the GGPA require investigation, and these are the main focus of the current study.

This study aims to specifically examine the characteristics of drought over the GGPA. It will also discuss the impact of severe droughts on the yield of four major crops (i.e. maize, rice, wheat, and soybean). The study is geared toward agricultural production and management, prevention and reduction of droughts, and the safeguarding of the global food security.

2. Data and methods

2.1. Standardized Precipitation Evapotranspiration Index

Drought variations were quantitatively evaluated using the Standardized Precipitation Evapotranspiration Index (SPEI) based on the Penman–Monteith equation (Beguería et al., 2014). The time series of the SPEI encompass 1951–2011 and the data is available from http://sac.csic.es/spei/. Among the SPEI data, the Penman-Monteith (PM) method was used to calculate the potential evapotranspiration; furthermore, the water balance of climate that would be suitable to study the effect of global warming on drought severity was considered within the dataset. Shorter accumulation periods (e.g. SPEI-3 and SPEI-6) were rated as sensitive to extreme, although longer periods (e.g. SPEI-24 and SPEI-48) typically missed relevant drought events. After considering SPEI-1 to SPEI-48, a medium-term accumulation period was finally selected to depict various world precipitation systems (SPEI-12, SPEI covering the time scale of 12 months) as recommended by Vicente-Serrano et al. (2010a). Details of the SPEI are introduced in the Data in Brief file (Section 1).

2.2. Land cover data and crop yield data

Global land cover data from 2000 (GLC2000) with a 5-min spatial resolution was obtained from the European Commission's Joint Research Center. It was separated into 22 types of land cover (Bartholome and Belward, 2005; Liu et al., 2017). To analyze drought across the major global grain producing areas in detail, we selected the 16th land type, which includes the global grain production area (including farmland) from around the world. The geographical positions split the global farmland into 18 global grain production regions (Fig. 2). A stable distribution of the global grain production area was assumed. Crop production in the global grain production areas was approximately equal to the grain output of the country. The crop yield data (from 1961 to 2011) of the specific countries were obtained from the Food and Agriculture Organization (FAO) (http://faostat.fao.org/).

2.3. Statistics indices

The Mann–Kendall (MK) method was used to investigate statistical trends of drought. Details for the MK method can be found in the Data in Brief file (Section 2). An additional linear regression method was used to analyze the trends of drought duration, area, severity, and frequency during the time series. The drought area was computed as the sum of the weighted (cosine function of latitude) grid area for the SPEI < -1.0. Drought durations were defined as the number of months with a SPEI < -1.0. The severity was defined as the absolute value of the integral area between the SPEI line and the horizontal axis (SPEI $= 0$) between the start month and the end month of the drought (Lei et al., 2015). The yield change percentage was used to measure the yield change during severe drought years. This was defined as:

$$\Delta_y = \frac{(y_t - \dot{y}_t)}{y_t} \times 100\%$$

where Δ_y represents the yield change percentage during the drought year; y_t represents the actual output during year t; $\dot{y}_t$ represents the polynomial fitting trend yield of year t. The polynomial fitting for each crop yield in each region is shown in the Data in Brief file (Fig. S1).

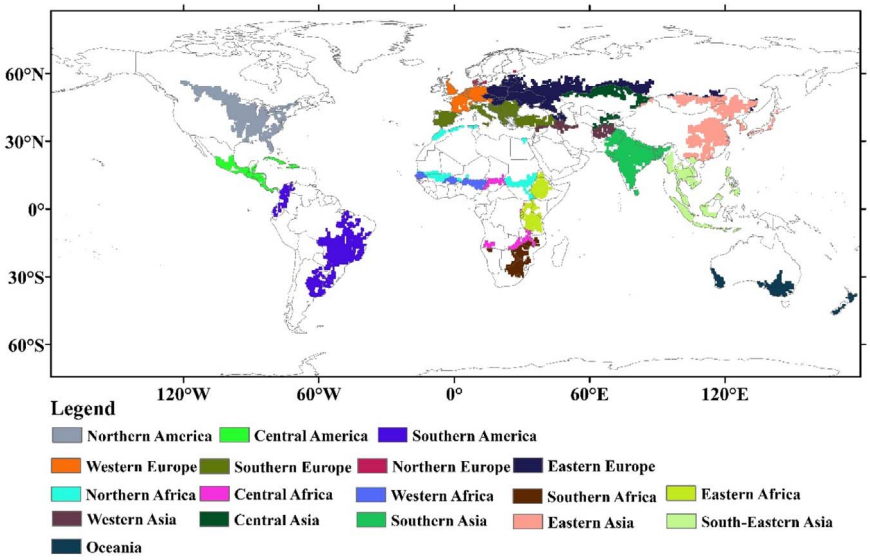

Fig. 2. Spatial pattern of global grain production area.

3. Results

3.1. Drought variation in GGPA

Fig. 3a depicts the spatial patterns of drought trends across the GGPA from 1951 to 2011. The major sections of the global agricultural area were characterized by decreasing SPEI, indicating that the drying tendency dominated major parts of the GGPA. This was consistent with previous findings that showed increased droughts across the world (Vicente-Serrano et al., 2010a; Dai, 2011). The global drying tendency could be caused by the increasing actual evaporation, due to increasing temperatures caused by global warming (Dai, 2011). This results in a decrease of soil moisture in the GGPA. The warm atmosphere could lead to a reduction in the number of wet days and increased length of dry spells, which could accelerate the increase of dry land and induce to drought (Giorgi et al., 2011). Northern Africa, Western Africa, central Southern Asia, and the north of Eastern Asia displayed a significant drying trend. Abnormal large-scale atmospheric circulation (e.g. El Niño-Southern Oscillation) and variations in the sea surface temperature were strongly associated with a decrease in rainfall. This became the main cause of the drying trend seen over Northern Africa, Western Africa, Southern Asia, and Eastern Asia (Dai and Wigley, 2000; Paeth et al., 2009; Hoerling et al., 2010; Boening et al., 2012). The increasing heat waves in Southern Asia that were accompanied by either low precipitation or the complete lack thereof, high evapotranspiration, or high moisture deficiency were important drivers for drought occurrence (Bandyopadhyay et al., 2016; Rohini et al., 2016). Land cover changes, such as decreased vegetational cover in Western and Northern Africa, resulted in increased near-surface warming and weakening of the hydrological cycle. This has been suggested as another factor to cause enhanced and prolonged droughts (Paeth et al., 2009). A significantly decreased trend of SPEI was identified in central Northern America. This indicated that few areas had a significant wet trend related to increased precipitation (Motha and Baier, 2005; Sheffield and Wood, 2010). This agreed with previous findings (Greve et al., 2014; Feng and Zhang, 2015).

Spatial patterns of drought severity and the frequency over GGPA are shown in Fig. 3b-c. Drought hot spots categorized by drought severity and frequency were typically located in the north of Eastern Asia, Western Africa, Northern Africa, central Southern Asia, and Central Europe. High drought frequency was observed in Western Africa, Northern Africa, Northern Europe, and Southern Asia. Central Eastern Asia, Northern America, and Western Asia were identified to have low drought frequency and few severity areas.

The temporal features of drought across the GGPA were also investigated (Fig. 4a-c). Generally, the GGPA showed a significant increase in drought duration, with an average of 2.2 dry months (Fig. 4a). Fig. 4b depicts an upward trend of the dry area over the GGPA, with an increasing rate of 1.109% per decade. Widespread droughts occurred in 1987, 2002, and 2007 with 25.8%, 28.9%, and 26.7% drought area. Drought severity was identified to follow a significantly increasing trend within the entire GGPA (Fig. 4c).

3.2. Characteristics of drought in each GGPA

The drought trends for each GGPA are listed in Table 1. Southern America followed a wet trend. A significant drought downtrend was detected in Northern America. Eastern Asia, Southern Europe, and Africa (except for Eastern Africa) displayed a significant drying trend. As shown in Fig. 5a, the drought severities of Southern Europe, Northern Africa, Central Africa, Western Asia, and Eastern Asia displayed a significant uptrend. Southern America, Northern America, and Eastern Africa displayed a significant decreasing trend (Fig. 5b). The other regions presented either a non-significant decrease or an increasing trend (Fig. 5c). Analysis of drought duration showed that Southern Europe, Northern Africa, Central Africa, Western Africa, Western Asia, Eastern Asia, and Oceania showed a significant increase of drought duration (Fig. 6a). Southern America and Northern America displayed a significant decreasing trend (Fig. 6b). There were no apparent changes distributed throughout the other grain production regions (Fig. 6c). Southern Europe recorded long drought durations and increased drought severity during the past two decades, with an average of 3.2 dry months. This was a result of increased atmospheric evaporative demand caused by increasing temperatures (Vicente-Serrano et al., 2014). In Northern and Western Africa, prolonged and severe droughts occurred in the mid 1980s. In 1984 the most severe drought occurred, with 9.5 and 10.8 dry months of the year.

Dry area changes that were observed over 18 grain production regions are shown in Fig. 7. According to Fig. 7a, Northern Africa showed a significant increasing trend of dry area at a rate of 5.28% per 10 years. Large drought areas covered Northern Africa in the mid 1980s. The most extensive drought occurred in 1984, where almost 80% was a drought area. A prominent drying trend occurred in Eastern Asia, Western Asia, and Western Africa at rates of 3.64% per 10 years, 3.21% per 10 years, and 3.18% per 10 years. Large and widespread droughts happened throughout Western Asia in 1971, 1999, 2000, 2001, and

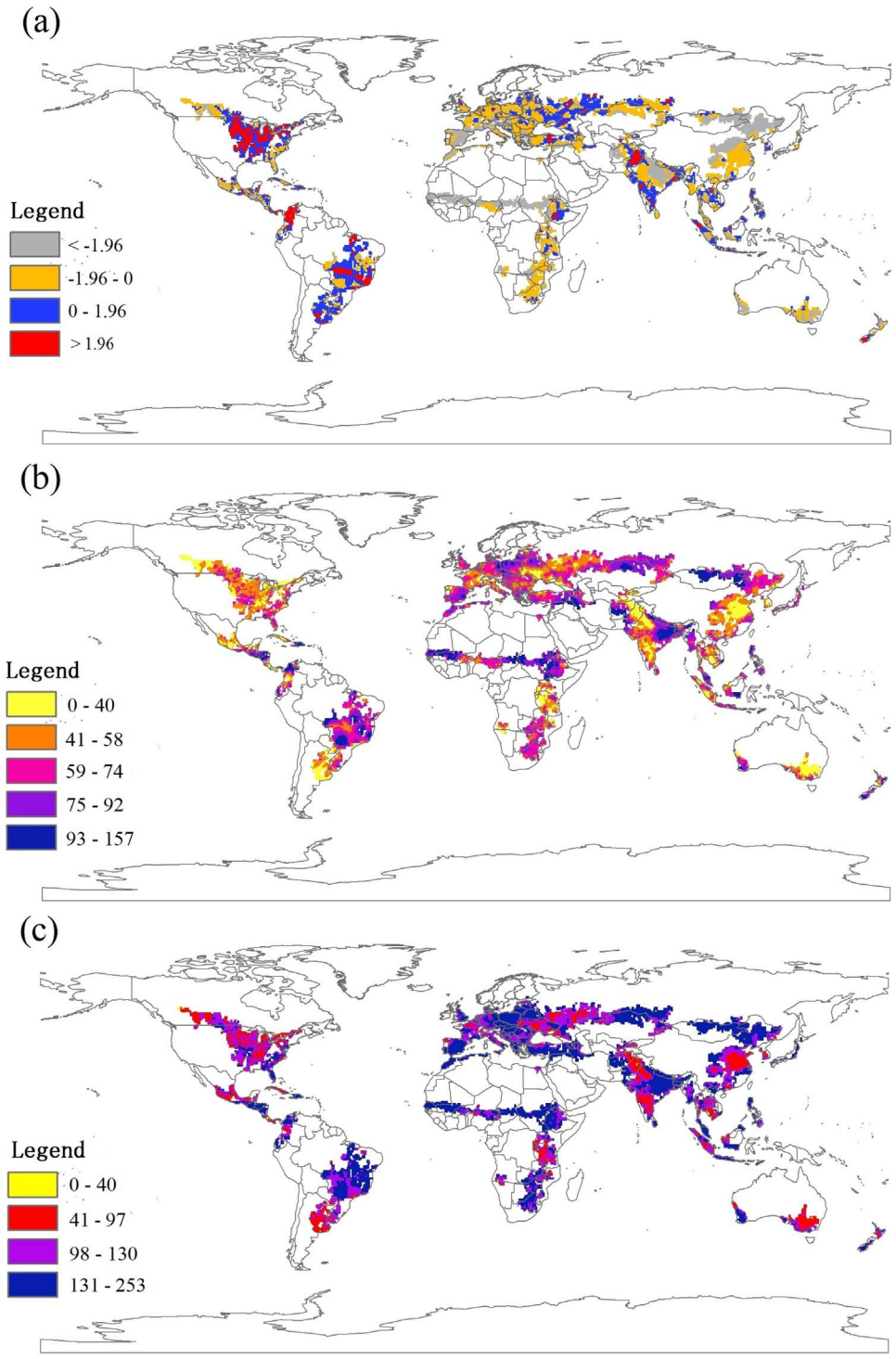

Fig. 3. Spatial characteristics of drought across global grain production area (GGPA). (a) Spatial pattern of drought trend: the numbers of the legend are Z values; positive values indicate increasing trend, or the opposite; if $|Z| \geqq 1.96$, the trend is significant at > 95% confidence level. (b) Drought severity: the number represents the total drought severity; the drought severity was defined as the absolute value of the integral area between the SPEI line and the horizontal axis (SPEI = 0) between the start month and the end month of the drought. (c) Drought frequency: the total drought frequency from 1951 to 2011.

2008 that covered more than 64% of the affected areas. Persistent multiyear droughts happened in Western Africa that dominated the mid 1980s, with 89% of drought areas in 1984. Central Africa, Southern Europe, and Southern Africa showed an increasing trend of dry areas with rates of 2.97% per 10 years, 2.67% per 10 years, and 2.16% per 10 years. There were intensive dry areas that covered more than 4% of Central Africa in the early 1980s and 1990s. The drought area percentages in Southern Africa reached almost 90% during 1992, and over 60% in 1973, 1983, and 1995. An extensive drought area covered Southern Europe over the two late decades, with more than 30% of the area affected by drought. Increasing trends of dry areas were also detected in Oceania, Western Europe, and Northern Europe at a rate of 1.89% per 10 years, 1.49% per 10 years, and 1.26% per 10 years. There was a decrease in dry areas in Northern America and Southern America at a rate of 1.51% per decade and 2.11% per decade, respectively (Fig. 7b). No obvious trend changes of dry areas were found for the other grain producing regions (Fig. 7c).

3.3. Effects of extreme drought on crop yield

Five typical extreme drought years were systematically selected according to area-weighted SPEI value, severity, duration, intensity,

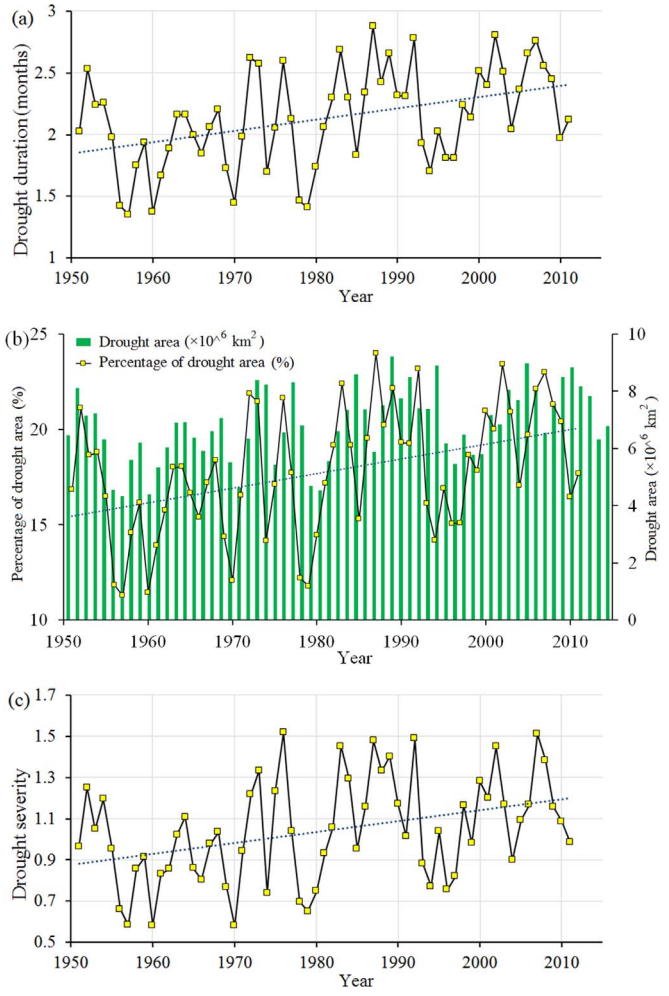

Fig. 4. Temporal features of drought across global grain production area (GGPA). (a) Temporal variation of drought duration: the drought durations were defined as the number of months that the SPEI < −1.0. (b) Percentage of drought area: the drought area was computed as the sum of the weighted (cosine function of latitude) grid area for the SPEI < −1.0. (c) Drought severity: the severity was defined as the absolute value of the integral area between the SPEI line and the horizontal axis (SPEI = 0) between the start month and the end month of the drought.

and impacted area (Data in Brief file, Table S1). The percentage crop yield anomalies under years of extreme drought were comparatively analyzed across the 18 grain production regions to quantitatively evaluate the impact of extreme drought on four major crop yields (maize, rice, wheat, and soybean).

Fig. 8a shows the yield change percentage in Africa for the four main crops during drought years. Overall, extreme drought events caused a large number of crop losses in Africa. There was an apparent decrease in Southern Africa (except maize), Middle Africa, and Western Africa during years of extreme drought. There was a significant decrease of crop yield in Southern America, a general decrease in Central America, and a general increase of crop yield in Northern America during periods of extreme drought except the year 1988 (Fig. 8b). The impact of extreme droughts on crop yield appeared diverse throughout Asia (Fig. 8c). The crop yield was generally increased during drought periods in Eastern Asia and was relatively stable in Western Asia; however, crop yield in Central Asia, Southern Asia, and South-Eastern Asia had lower yields under extreme droughts. In Europe, the crop yield primarily followed an increasing trend during extreme drought periods (Fig. 8d). There was an obvious increase of crop yield in Eastern Europe, Northern Europe, and Southern Europe, indicating that the crop yield was relatively unaffected by extreme droughts. Except for individual crop, the yield in Oceania showed a general increase (Fig. 8e). The statistical frequency and proportion of five typical extreme drought years in the developing/developed countries and regions were also concluded in Table 2.

Accordingly, the data suggests that developing countries and regions (e.g. Southern Africa, Middle Africa, Northern Africa, Central Asia, Southern Asia, South-Eastern Asia, Southern America, and Central America) are generally more susceptible to extreme droughts and suffered more losses than developed countries and regions (Europe, Oceania, Eastern Asia, and Northern America), which is an interesting finding.

4. Discussion

The findings of this study address the trend of global drought as it pertains to climate change. There has been controversial debate and while some studies argue for a stronger tendency towards global drought, others argue against it. Our results were derived from a comprehensive quantitative index (i.e. SPEI) that indicated an increasing trend of drought across the GGPA. The results were in accordance with the thought of a tendency towards increasing global drought, which was consistent with the observed global drought numbers and economic losses (Fig. 1). As mentioned in the Introduction section, the controversial debate mainly derived from the usage of different climatic datasets and drought metrics. For instance, two common metrics, the Standardised Precipitation Index (SPI) and the self-calibrated Palmer Drought Severity Index (scPDSI), enable measurement of both wetness and dryness. However, the SPI is only based on precipitation data and does not consider other critical variables (such as evapotranspiration), which significantly influences drought conditions. Actually, the study of Abramopoulos et al. (1988) has already revealed that evaporation and transpiration can consume up to 80% of rainfall, suggesting that the drought conditions based on SPI may be questionable to a certain extent. Additionally, the fraction of drying due to temperature anomalies is as high as that attributable to rainfall shortage; therefore, it is preferable to utilize drought metrics that consider the temperature factor in the formulation of datasets such as the scPDSI; however, the scPDSI lacks multi-scalar characteristics that are essential for determining the effect of droughts on different hydrological systems, crops, natural vegetation, and for differentiating among various drought types (Vicente-Serrano et al., 2010b). Based on precipitation and potential evapotranspiration (PET), the SPEI proposed by Vicente-Serrano et al. (2010a) manages to combine the sensitivity of the scPDSI to changes in evaporation demand (caused by temperature fluctuations and trends) with the multi-temporal nature of the SPI, which can better overcome the above-mentioned advantages. Accordingly, the drought analysis of GGPA measured via SPEI is more

Table 1
Temporal trend of drought in 18 global grain production regions.

Region	Northern America	Central America	Southern America	Western Europe	Southern Europe	Northern Europe	Eastern Europe	Northern Africa	Central Africa
MK	2.36	−0.14	1.52	−1.28	−2.31	−1.12	−0.33	−5.51	−4.08
Region	Western Africa	Southern Africa	Eastern Africa	Western Asia	Central Asia	Southern Asia	Eastern Asia	South-Eastern Asia	Oceania
MK	−4.21	−2.16	−1.80	−1.51	−0.73	−1.12	−5.47	−0.04	−1.72

Note: Positive values indicate increasing dry trend, or the opposite. If |MK value| ≧ 1.96, then the dry or wet trend is significant at > 95% confidence level.

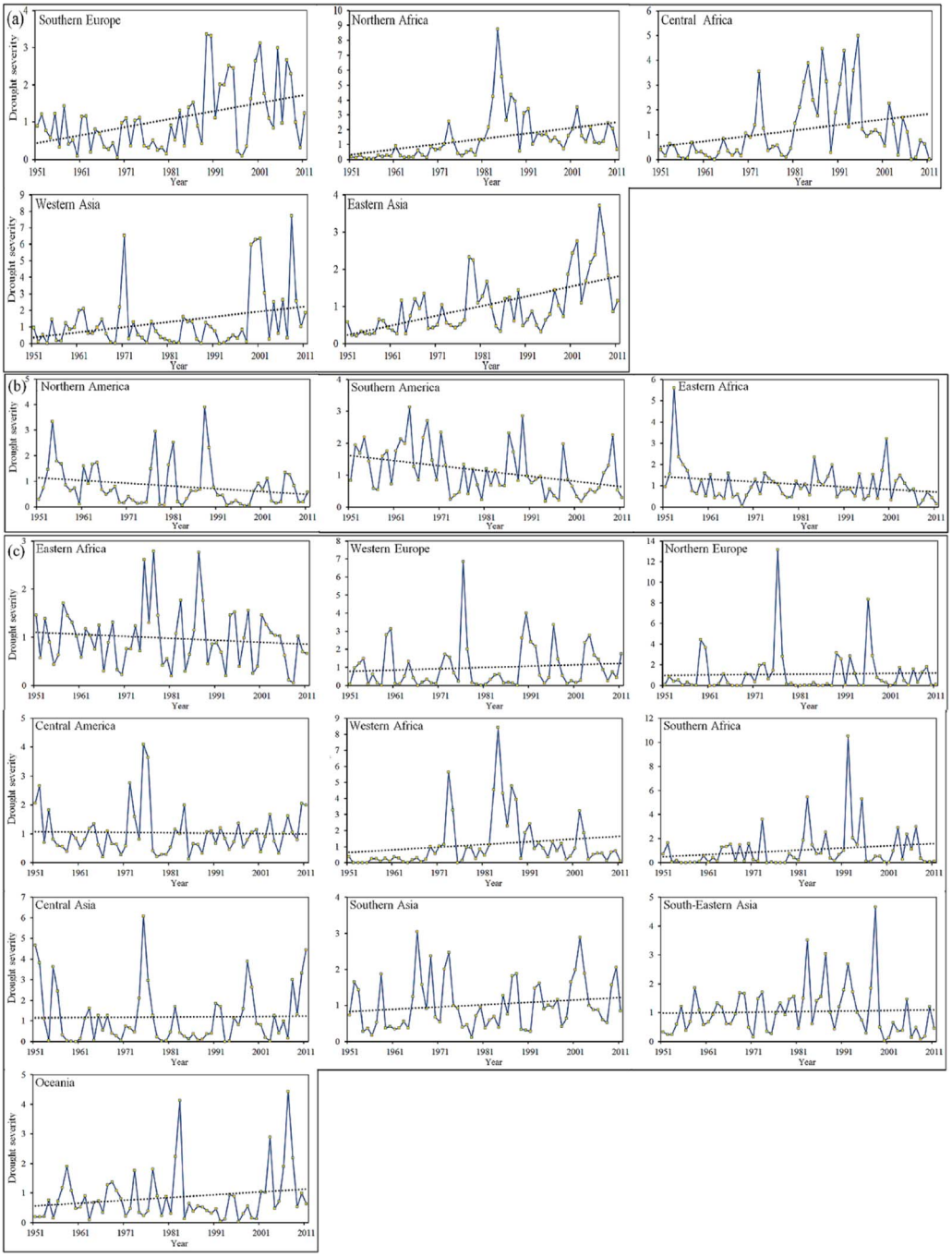

Fig. 5. Temporal change of drought severity across the 18 grain production regions during 1951–2011: with (a) significant uptrend, (b) significant downtrend, and (c) non-significant change.

preferable and reasonable.

The other issue of this study concerns the spatial pattern of the impacts of global drought on crop yield. Our results demonstrated a considerable variation in crop yields across different countries and regions during the past several decades, where increased droughts occurred. Developing countries and regions were generally more susceptible to droughts and suffered more losses than developed countries and regions. This significant regional variation was a manifestation of both heterogeneous adaptive capacity and resilience in the context of the prevalence of global drought. Main reasons that may account for such a variation as well as response measures that could mitigate the adverse impacts of global drought are discussed in the following sections.

4.1. Limited adaptive capacity in developing countries

Although the increase of droughts (due to climate change) is a global phenomenon, its impacts on crop yield and food security varied across regions. Our results suggested that food production in developing countries was more vulnerable to disturbances and sudden changes of water variability compared to developed countries. To explore the food insecurity in developing countries as a result of climate change, we unpacked the multifaceted concept of adaptive capacity from perspectives of technology and governance. Our discussion focuses primarily on smallholder farming systems (e.g. less than five ha in size), which were the dominant agricultural models seen in most developing regions (Müller et al., 2011; Lowder et al., 2016).

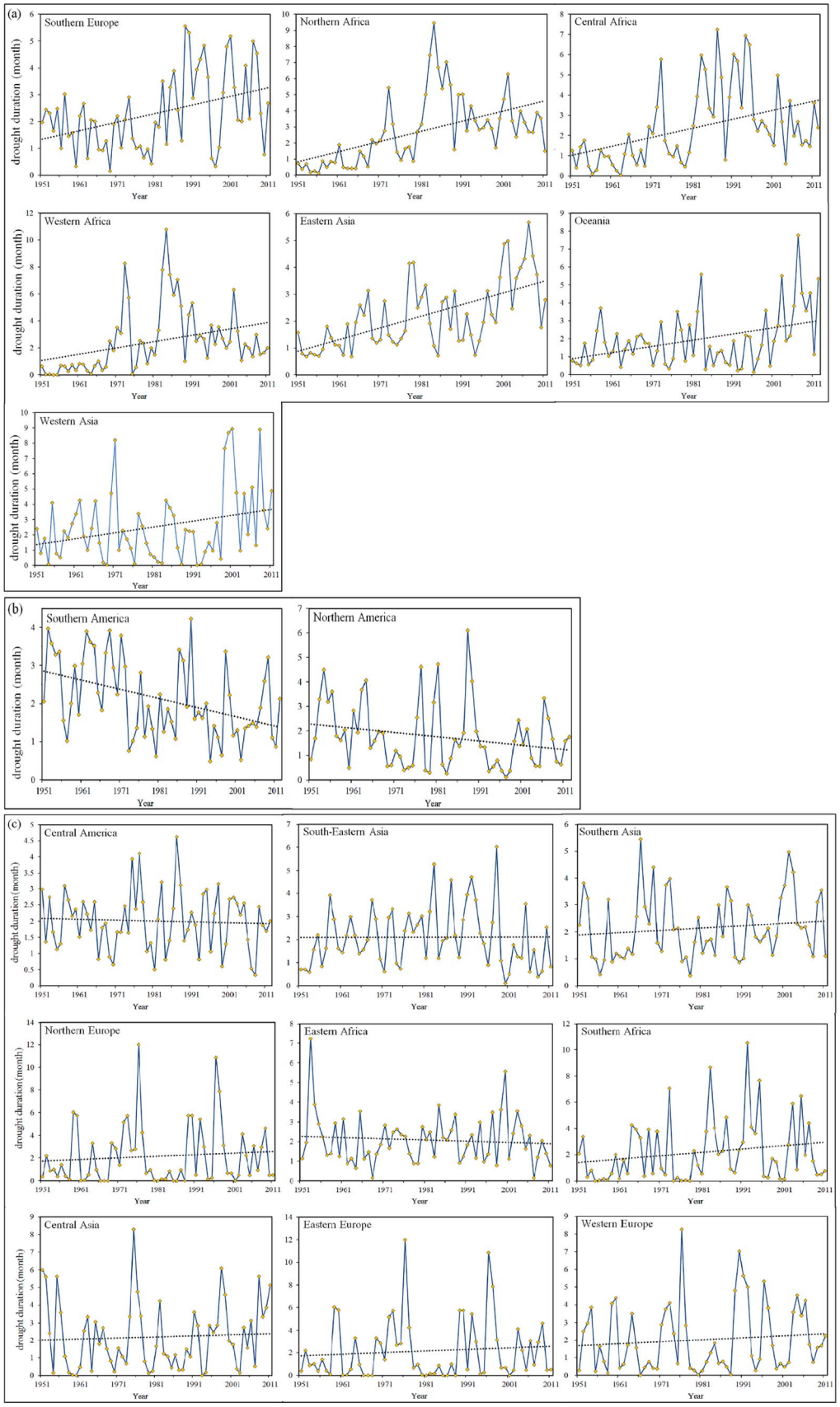

Fig. 6. Temporal change of drought duration across the 18 grain production areas during 1951–2011: with (a) significant uptrend, (b) significant downtrend, and (c) non-significant change.

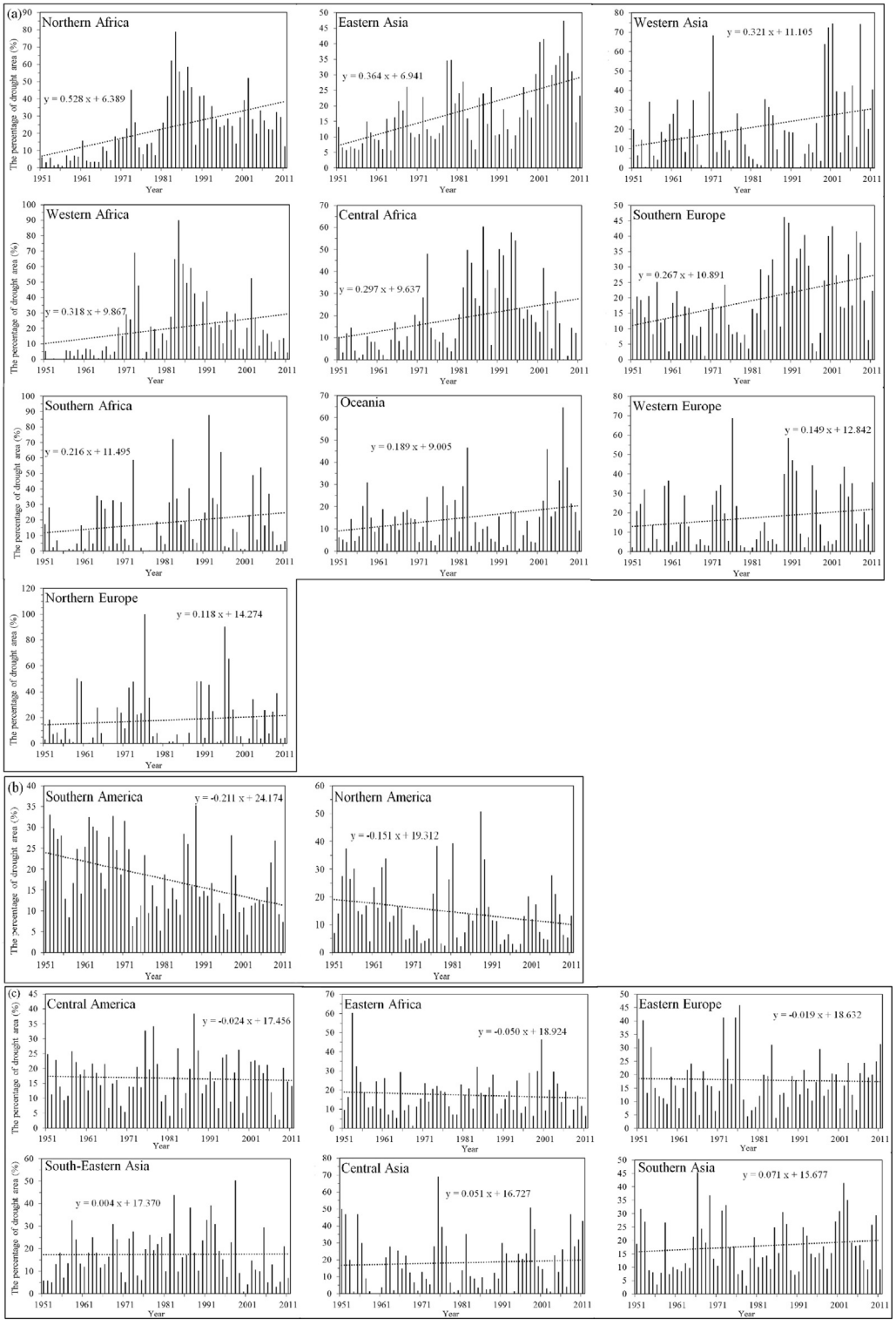

Fig. 7. Temporal changes of dry area across the 18 grain production areas during 1951–2011: with (a) significant uptrend, (b) significant downtrend, and (c) non-significant change.

4.1.1. Technical capacity

Technology is the most direct instrument for crop yield stability against natural hazards and climate change. The farming techniques of small farms in most of the developing regions (i.e. Sub-Saharan Africa and South Asia) remain relatively basic (Knox, 2012). In fact, the inadequate technical capacity of developing regions is not about technologies per se, but it is a reflection of the numerous intertwined socio-economic constraints.

Warm temperature is a major threat associated with droughts. Increasing temperatures are often accompanied by an environment that is conducive for insect development and reproduction. Some researchers have reported that outbreaks of aggressive insect attacks were closely related to temperature (Hicke et al., 2006; Rouault et al., 2006). This could increase the pressure of pest infestation on crop yield when the tendency for drought increases (Rouault et al., 2006; Allen et al., 2010). Although seasonal forecasting could reduce the risk of drought by enabling farmers to timely implement suitable adjustments (Dorward et al., 2015), small farms often plan their livelihood options

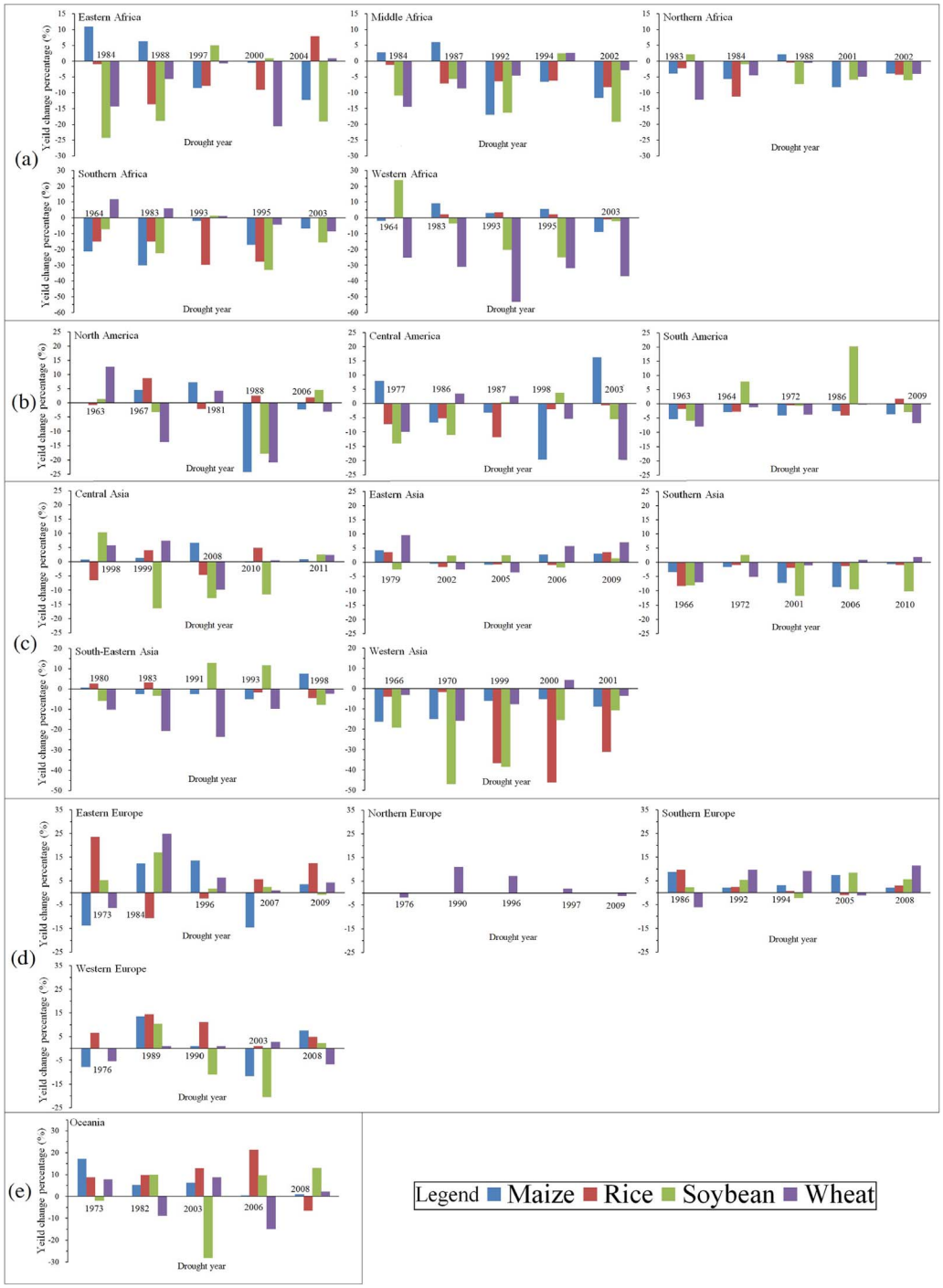

Fig. 8. Yield change percentage of the four main crops in each grain production region during extreme drought years: (a) Africa, (b) America (c) Asia, (d) Europe, and (e) Oceania. The negative/positive values of ordinate represent the decrease/increase of crop yield during the typical drought event. The number in the abscissa represents the typical drought year.

based on long-term climate and weather information and they may have difficulty adjusting production operations (e.g. planting) according to effective, comprehensible, and accessible weather forecasts over weeks, months, and years (Donald et al., 2016). Moreover, small farms often lack the financial capacity to increase agricultural inputs (i.e. use drought tolerant seeds) that are required to mitigate the impact of drought-induced pests on agriculture. The adaptive capacity for those who have received aid from international agencies or developed countries remains limited. For example, the Green Revolutions provided free fertilizer-responsive high-yielding seeds to smallholder farms in Sub-Saharan Africa (Larson et al., 2016). This improved the local capacity to resist drought stress to a certain extent; however, the lack of other important technologies (such as hydro-infrastructure) dwarfed the effects of the technical support. Without sufficient funds to build and maintain rural agricultural infrastructure, such as small reservoirs and irrigation channels (Olesen et al., 2011), smallholder farms in developing regions are unable to maintain a stable water supply for crops during climatic and seasonable fluctuations in water availability (Challinor et al., 2007). This results in the occurrence of extreme drought, which remains a tremendous challenge for food security, despite the provision of technologies from other regions and agencies.

4.1.2. Governance capacity

The limited governance capacity is an indirect, yet profound reason

Table 2
Statistical frequency and proportion of five typical extreme drought years.

Region	Crop	Maize		Rice		Soybean		Wheat	
	Change	Fre.	Pro.	Fre.	Pro.	Fre.	Pro.	Fre.	Pro.
Developing areas	Increased	17	30.91%	12	21.82%	15	27.27%	14	25.45%
	Decreased	38	69.09%	43	78.18%	40	72.73%	41	74.55%
Developed areas	Increased	22	73.33%	21	70%	20	66.67%	20	57.14%
	Decreased	8	26.67%	9	30%	10	33.33%	15	42.86%

Note: Developing areas include Eastern Africa, Middle Africa, Northern Africa, Southern Africa, Western Africa, Central Asia, Southern Asia, South-Eastern Asia, Western Asia, Central America, and South America; developed areas include Eastern Europe, Northern Europe, South Europe, Western Europe, Eastern Asia, North America, and Oceania. The frequency (Fre.) was counted by adding up all the Increased/Decreased number in the corresponding areas. The Increased proportion is calculated by 'Increased Fre./ (Increased Fre. + Decreased Fre.) × 100%', and the Decreased proportion can be deduced by analogy.

for the vulnerability to climate change. The limited governance capacity is reflected both at local and at regional level within developing countries. The scarcity of water resources creates local challenges for sustainable water use. This requires normative governance principles such as polycentricism, participation, transparency, responsiveness, equality, and accountability. A variety of social issues (that center on conflicts) arise from 'The Tragedy of the Commons' that remain prevalent across the world. The failure to cooperate, as well as inadequate governance capacity poses a severe threat to developing countries (World Bank, 2005). In these countries, the livelihoods of many smallholders solely depend on rain-fed agriculture (Downing et al., 1997; Knox, 2012), as they have little or no access to water resources (World Bank, 2009). Rapid population growth and economic development in these underdeveloped areas further increased the pressure for water availability. The lack of policy instruments to effectively, efficiently, and fairly distribute limited water resources is the main reason for the intensifying water conflicts among water users and for their vulnerability to severe drought. The low efficiency of water use and land resources forms a further limitation that smallholder farms face with drought resistance, particularly for developing regions in West Asia and North Africa (Barrett and Palm, 2016). Low efficiency is embedded in technical inadequacy, which is attributable to a weak governance system, where efficient water use and water conservation are not fully encouraged through institutional means. This results in further reduced agricultural water resources due to groundwater overexploitation and water pollution. For the poor and for smallholders, addressing the risk of drought thus requires better use of local knowledge and increased efforts of adaptation as agricultural water availability decreases (Fox et al., 2013).

The effective institutional arrangements and policy instruments for alleviating the impact of climate change remain inadequate at a regional scale. The policymakers in some developing regions are unable to make informed decisions on planning, regulations, and legal reform due to a lack of knowledge and information. Additionally, a growing number of studies have identified a gap between policy-making and policy implementation (Campbell et al., 2016). Despite their good intentions, various practical constraints have hindered the efficacy of adaptation polices that would combat climate change. Studies have suggested institutional mismatch between the characteristics of institutions and the socio-economic context that they operate on as the main cause of institutional failure (Young, 2002). Other factors such as corruption, opportunism, and flawed enforcement mechanisms are also key limitations faced by developing countries in their fight to reduce drought stress.

4.2. Mitigation measures

The current results, as well as past studies, have suggested that droughts will likely become more frequent. This will likely result in the occurrence of food supply shortages and food price spikes in the near future. This is due to a reduction of crop yields, which could further exacerbate food uncertainty and even cause social and political instability in developing regions. Mitigation measures are necessary to improve the adaptive capacity and resilience of agricultural systems in developing regions.

Technological developments (i.e. new crop varieties and weather climate systems) that are boosted by additional agricultural technical inputs are among the most direct and effective ways to manage drought risks. Developed regions have benefited dramatically over the past century from the development of new crops, although a majority of the developing regions lag behind (Reidsma et al., 2010; Lybbert and Sumner, 2012). These new crop varieties offer flexible crop choices that are more suitable to local climatic conditions, while requiring less fertilizer and pesticides. This is particularly important for poor smallholder farms, which could adapt to pests, diseases, and drought stress. The positive impacts of agricultural technology could be enhanced by a promotion of education and training for farmers (Rosegrant and Cline, 2003). The development of weather information systems has demonstrated its potential and proven to be an effective instrument to help smallholder farms in adapting to drought risk (Chuku and Okoye, 2009). This system could forecast different meteorological factors (i.e. temperature, precipitation, and atmospheric circulation) that are correlated with drought occurrences. Abnormal atmospheric circulation caused by El Niño and La Niña generally result in frequent and severe droughts. Although the effective use of this weather information system is often constrained by the availability and comprehensiveness of forecasts at different timing and scale, evidence suggests that proper technical guidance and inter-institutional collaboration could assist smallholder farmers in preparing for and taking actions against implications of climate variability (Cooper et al., 2008).

In addition to technological investments, developing agricultural infrastructures are important when mitigating drought risks. Small reservoirs could harvest water during the wet season to offset fluctuations in water availability throughout the drought period. Anti-seepage irrigation channels could circumvent water wastage during transportation and improve the efficiency of agricultural water use. However, financial capacity is a large constraint within developing regions when constructing such agricultural infrastructures. Humanitarian or financial assistance provided by developed countries or global institutions (e.g. World Bank and FAO) could be an effective short-term response to food security issues caused by drought stress.

Policies designed by the government or non-governmental organizations (NGOs) are critical and offer a basic foundation for the promotion and implementation of technical measures at various scales (Fan and Brzeska, 2016). For example, the success of the Green Revolutions could not have been achieved without favorable policies that promoted investments in agricultural technological innovation, infrastructure construction, and offered loans to smallholder farms (Hazell, 2009). The International Crops Research Institute For The Semi-arid Tropics (ICRISAT) also suggested that improved water governance innovations and the re-targeting and re-development of existing knowledge about crops, soil, and water could substantially mitigate the

negative impacts of increasing temperatures (Cooper et al., 2009). By improving the governance structure (i.e. legal framework reform and institutional innovation), this would allow smallholder farms to adjust for more severe drought risks. This would also allow for adjustments in response to increasing water demand induced by population growth, water loss, and water pollution. This could provide a profound contribution in the promotion for effective adaptive capacity of the developing regions in light of climate change.

5. Conclusions

Our study analyzed drought variations across the GGPA by analyzing the SPEI dataset from 1951 to 2011. The impact of severe droughts on the yields of four major crops (maize, rice, wheat, and soybean) was investigated. Our results confirmed that a majority of the GGPA had a drying tendency due to global warming. The entire GGPA had significantly increased drought durations, drought areas, and drought severities. It is therefore paramount that decision-makers and international organizations pay more attention to the effects of the drying tendency in the GGPA. Our study indicated that the crop yield in most developing countries or regions is more easily influenced by extreme drought than in developed countries. This suggests that global food security is closely associated with the way that developing regions adapt to drought disasters. Food security could be ensured in these regions by including technological investments, construction and improvement of infrastructures, governance reforms, as well as financial and technical assistance from developed regions. The sustainable concern on meteorological disasters (e.g. drought and flood) caused by climate change and their effects on crop yield could lead to significant progress to achieve global food security. The findings in this study provide useful information for regional decision-makers and international organizations in their efforts to ensure food security and to maintain socio-political stability.

Acknowledgements

The research is financially supported by the National Natural Science Foundation of China (Grant No.51579105, 51709117, 91547202, 51479216); China Postdoctoral Science Foundation (2017M612662); the Science and Technology Program of Guangzhou City (201707010072); the Science and Technology Planning Project of Guangdong Province, China (2017A040405020); the special fund of water resources conservation and protection of Guangdong Province (2017). Our cordial gratitude also should be owed to the Editor Prof. Derek Byerlee and Prof. Achim Dobermann, and the two anonymous reviewers for their professional and pertinent suggestions and comments, which are greatly helpful for further improvements of the quality of this manuscript.

Conflict of interest statement

No conflict of interest exits in the submission of this manuscript, and manuscript is approved by all authors for publication. I would like to declare on behalf of my co-authors that the work described was original research that has not been published previously, and not under consideration for publication elsewhere, in whole or in part. All the authors listed have approved the manuscript that is enclosed.

References

Abramopoulos, F., Rosenzweig, C., Choudhury, B., 1988. Improved ground hydrology calculations for global climate models (GCMs): soil water movement and evapotranspiration. J. Clim. 1, 921–941.

Allen, C.D., Macalady, A.K., Chenchouni, H., Bachelet, D., McDowell, N., Vennetier, M., Gonzalez, P., 2010. A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. For. Ecol. Manag. 259 (4), 660–684.

Asseng, S., Ewert, F., Rosenzweig, C., Jones, J.W., Hatfield, J.L., Ruane, A.C., Brisson, N., 2013. Uncertainty in simulating wheat yields under climate change. Nat. Clim. Change 3 (9), 827–832.

Bandyopadhyay, N., Bhuiyan, C., Saha, A.K., 2016. Heat waves, temperature extremes and their impacts on monsoon rainfall and meteorological drought in Gujarat, India. Nat. Hazards 82 (1), 367–388.

Barrett, C.B., Palm, C., 2016. Meeting the global food security challenge: obstacles and opportunities ahead. Glob. Food Secur. 11, 1–4.

Bartholome, E.M., Belward, A.S., 2005. A new approach to global land cover mapping from earth observation data. Int. J. Remote Sens. 26 (9), 1959–1977.

Beguería, S., Vicente-Serrano, S.M., Reig, F., Latorre, B., 2014. Standardized precipitation evapotranspiration index (SPEI) revisited: parameter fitting, evapotranspiration models, tools, datasets and drought monitoring. Int. J. Climatol. 34 (10), 3001–3023.

Boening, C., Willis, J.K., Landerer, F.W., Nerem, R.S., Fasullo, J., 2012. The 2011 La Niña: so strong, the oceans fell. Geophys. Res. Lett. 39 (19).

Campbell, B.M., Vermeulen, S.J., Aggarwal, P.K., Corner-Dolloff, C., Girvetz, E., Loboguerrero, A.M., Wollenberg, E., 2016. Reducing risks to food security from climate change. Glob. Food Secur. 11, 34–43.

Cooper, P.J.M., Dimes, J., Rao, K.P.C., Shapiro, B., Shiferaw, B., Twomlow, S., 2008. Coping better with current climatic variability in the rain-fed farming systems of sub-Saharan Africa: an essential first step in adapting to future climate change? Agric. Ecosyst. Environ. 126 (1–2), 24–35.

Cooper, P., Rao, K.P.C., Singh, P., Dimes, J., Traore, P.S., Rao, K., Dixit, P., Twomlow, S.J., 2009. Farming with current and future climate risk: advancing a hypothesis of hope' for rainfed agriculture in the semi-arid tropics. J. Sat. Agric. Res. 7, 1–19.

Challinor, A., Wheeler, T., Garforth, C., Craufurd, P., Kassam, A., 2007. Assessing the vulnerability of food crop systems in Africa to climate change. Clim. Change 83 (3), 381–399.

Chen, H., Sun, J., 2015. Changes in drought characteristics over china using the standardized precipitation evapotranspiration index. J. Clim. 28 (13), 281–299.

Chuku, C.A., Okoye, C., 2009. Increasing resilience and reducing vulnerability in sub-Saharan African agriculture: strategies for risk coping and management. Afr. J. Agric. Res. 4 (11), 1524–1535.

Cook, B.I., Smerdon, J.E., Seager, R., Coats, S., 2014. Global warming and 21st century drying. Clim. Dyn. 43 (9–10), 2607–2627.

Dai, A., Wigley, T.M.L., 2000. Global patterns of Enso-induced precipitation. Geophys. Res. Lett. 27 (9), 1283–1286.

Dai, A., 2011. Drought under global warming: a review. Wiley Interdisc. Rev. Clim. Change 2 (1), 45–65.

Dai, A., 2013. Increasing drought under global warming in observations and models. Nat. Clim. Change 3 (1), 52–58.

Deo, R.C., Byun, H.R., Adamowski, J.F., Begum, K., 2017. Application of effective drought index for quantification of meteorological drought events: a case study in Australia. Theor. Appl. Climatol. 128, 359–379.

Donald, F.L., Rie, M., Keijiro, O., 2016. Why African rural development strategies must depend on small farms. Glob. Food Secur. 10, 39–51.

Dorward, P., Clarkson, G., Stern, R., 2015. Participatory Integrated Climate Services for Agriculture (PICSA): Field Manual. Walker Institute, University of Reading. ISBN: 9780704915633.

Downing, T.E., Ringius, L., Hulme, M., Waughray, D., 1997. Adapting to climate change in Africa. Mitig. Adapt. Strateg. Glob. Change 2 (1), 19–44.

EM-DAT. Disaster Profiles. The OFDA/CRED international disaster database. 〈http://www.emdat.be/database〉 (Accessed 19 December 2016).

Fan, S., Brzeska, J., 2016. Sustainable food security and nutrition: demystifying conventional beliefs. Glob. Food Secur. 11, 11–16.

Feng, H., Zhang, M., 2015. Global land moisture trends: drier in dry and wetter in wet over land. Sci. Rep. 5.

Fox, L., Haines, C., Munoz, J.H., Thomas, A.H., 2013. Africa's got work to do: employment prospects in the new century. Imf Work. Pap. 13 (201).

Geng, G., Wu, J., Wang, Q., Lei, T., He, B., Li, X., Liu, D., 2016. Agricultural drought hazard analysis during 1980–2008: a global perspective. Int. J. Climatol. 36 (1), 389–399.

Giorgi, F., Im, E.S., Coppola, E., Diffenbaugh, N.S., Gao, X.J., Mariotti, L., Shi, Y., 2011. Higher hydroclimatic intensity with global warming. J. Clim. 24 (20), 5309–5324.

Greve, P., Orlowsky, B., Mueller, B., Sheffield, J., Reichstein, M., Seneviratne, S.I., 2014. Global assessment of trends in wetting and drying over land. Nat. Geosci. 7 (10), 716.

Hazell, P.B., 2009. Transforming agriculture: the green revolution in Asia. Millions fed: Proven successes in agricultural development, 25-32.

Hicke, J.A., Logan, J.A., Powell, J., Ojima, D.S., 2006. Changing temperatures influence suitability for modeled mountain pine beetle (Dendroctonus ponderosae) outbreaks in the western United States. J. Geophys. Res.: Biogeosci. 111 (G2).

Hoerling, M., Eischeid, J., Perlwitz, J., 2010. Regional precipitation trends: distinguishing natural variability from anthropogenic forcing. J. Clim. 23 (23), 2131–2145.

Knox, J., 2012. Climate change impacts on crop productivity in Africa and South Asia. Environ. Res. Lett. 7 (3), 34032–34039.

Larson, D.F., Muraoka, R., Otsuka, K., 2016. Why African rural development strategies must depend on small farms. Glob. Food Secur. 10, 39–51.

Lei, T., Wu, J., Li, X., Geng, G., Shao, C., Zhou, H., Liu, L., 2015. A new framework for evaluating the impacts of drought on net primary productivity of grassland. Sci. Total Environ. 536, 161–172.

Lesk, C., Rowhani, P., Ramankutty, N., 2016. Influence of extreme weather disasters on global crop production. Nature 529 (7584), 84–87.

Liu, X., Liang, X., Li, X., Xu, X., Ou, J., Chen, Y., Li, S., Wang, S., Pei, F., 2017. A future land use simulation model (FLUS) for simulating multiple land use scenarios by coupling human and natural effects. Landsc. Urban Plan 168, 94–116.

Lobell, D.B., Schlenker, W., Costa-Roberts, J., 2011. Climate trends and global crop

production since 1980. Science 333 (6042), 616–620.
Lowder, S.K., Skoet, J., Raney, T., 2016. The number, size, and distribution of farms, smallholder farms, and family farms worldwide. World Dev. 87, 16–29.
Lybbert, T.J., Sumner, D.A., 2012. Agricultural technologies for climate change in developing countries: policy options for innovation and technology diffusion. Food Policy 37 (1), 114–123.
Mishra, A.K., Singh, V.P., 2010. A review of drought concepts. J. Hydrol. 391 (1–2), 202–216.
Motha, R.P., Baier, W., 2005. Impacts of present and future climate change and climate variability on agriculture in the temperate regions: north America. Clim. Change 70 (1), 137–164.
Müller, C., Cramer, W., Hare, W.L., Lotze-Campen, H., 2011. Climate change risks for African agriculture. Proc. Natl. Acad. Sci. 108 (11), 4313–4315.
Olesen, J.E., Trnka, M., Kersebaum, K.C., Skjelvåg, A.O., Seguin, B., Peltonen-Sainio, P., Micale, F., 2011. Impacts and adaptation of European crop production systems to climate change. Eur. J. Agron. 34 (2), 96–112.
Paeth, H., Born, K., Girmes, R., Podzun, R., Jacob, D., 2009. Regional climate change in tropical and northern Africa due to greenhouse forcing and land use changes. J. Clim. 22 (1), 114–132.
Piao, S., Ciais, P., Huang, Y., Shen, Z., Peng, S., Li, J., 2010. The impacts of climate change on water resources and agriculture in china. Nature 467 (7311), 43.
Ray, D.K., Gerber, J.S., MacDonald, G.K., West, P.C., 2015. Climate variation explains a third of global crop yield variability. Nat. Commun. 6.
Reidsma, P., Ewert, F., Lansink, A.O., Leemans, R., 2010. Adaptation to climate change and climate variability in European agriculture: the importance of farm level responses. Eur. J. Agron. 32 (1), 91–102.
Rohini, P., Rajeevan, M., Srivastava, A.K., 2016. On the variability and increasing trends of heat waves over India. Sci. Rep. 6.
Rosegrant, M.W., Cline, S.A., 2003. Global food security: challenges and policies. Science 302 (5652), 1917–1919.
Rouault, G., Candau, J.N., Lieutier, F., Nageleisen, L.M., Martin, J.C., Warzée, N., 2006. Effects of drought and heat on forest insect populations in relation to the 2003 drought in Western Europe. Ann. For. Sci. 63 (6), 613–624.
Sheffield, J., Wood, E.F., 2010. Global trends and variability in soil moisture and drought characteristics, 1950–2000, from observation-driven simulations of the terrestrial hydrologic cycle. J. Clim. 21 (3), 432–458.
Sheffield, J., Wood, E.F., Roderick, M.L., 2012. Little change in global drought over the past 60 years. Nature 491, 435–438.
Trenberth, K.E., Dai, A., Schrier, G.V.D., 2013. Global warming and changes in drought. Nat. Clim. Change 4 (1), 17–22.
Vicente-Serrano, S.M., Beguería, S., López-Moreno, J.I., Angulo, M., El Kenawy, A., 2010a. A new global 0.5 degrees gridded dataset (1901–2006) of a multiscalar drought index: comparison with current drought index datasets based on the Palmer Drought Severity Index. J. Hydrometeorol. 11 (4), 1033–1043.
Vicente-Serrano, S.M., Beguería, Santiago, López-Moreno, Juan I., 2010b. A multi-scalar drought index sensitive to global warming: the standardized precipitation evapotranspiration Index - SPEI. J. Clim. 23, 1696–1718.
Vicente-Serrano, S.M., Lopez-Moreno, J.I., Beguería, S., Lorenzo-Lacruz, J., Sanchez-Lorenzo, A., García-Ruiz, J.M., Coelho, F., 2014. Evidence of increasing drought severity caused by temperature rise in southern Europe. Environ. Res. Lett. 9 (4), 044001.
Wheeler, T., Von Braun, J., 2013. Climate change impacts on global food security. Science 341 (6145), 508–513.
World Bank, 2009. Agriculture and Rural Sector South Asia: Shared Views on Development and Climate Change. World Bank, Washington, DC, pp. 97–107.
World Bank. Agriculture, & Rural Development Dept, 2005. Shaping the Future of Water For Agriculture: A Sourcebook for Investment in Agricultural Water Management. World Bank Publications.
Young, O.R., 2002. The Institutional Dimensions of Environmental Change: Fit, Interplay, and Scale. MIT Press, Cambridge, Massachusetts.